



IMPACT OF WIND AND SOLAR RENEWABLE ENERGY PRODUCTION ON THE ENVIRONMENT. CASE STUDIES IN ROMANIA

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Abstract. *Renewable energy technologies play an essential role in reducing environmental impacts associated with conventional energy production. Among these technologies, wind and solar photovoltaic (PV) systems are widely deployed, yet their overall performance depends on both environmental and economic factors. This study evaluates the environmental and economic impacts of wind and solar photovoltaic (PV) energy systems using Life Cycle Assessment (LCA) and Levelized Cost of Energy (LCOE) methodologies. The analysis considers the entire life cycle of the systems, including manufacturing, operation, and end-of-life stages. To illustrate the results, two large-scale case studies representative of Romanian conditions are analyzed: a 100 MW PV system and a 99 MW wind energy system. The findings highlight differences in impact profiles and cost structures between the two technologies, emphasizing the importance of integrated environmental and economic assessment in renewable energy planning and decision-making.*

Keywords: renewable energy, wind power, solar energy, LCA, LCOE, environmental impact, Romania

1. INTRODUCTION

The rapid economic development and urbanization of the last century have led to a substantial increase in global energy demand. This growth has been largely supported by the intensive use of fossil fuels, resulting in significant greenhouse gas emissions and severe environmental impacts. As a consequence, climate change has become one of the most critical challenges facing modern societies. In response to these challenges, the transition toward renewable energy sources has become a central objective of global and European energy policies. Renewable technologies such as wind and solar photovoltaic (PV) systems play a key role in reducing carbon emissions, enhancing energy security, and supporting sustainable development. These technologies have gained increasing attention due to their declining costs, technological maturity, and large-scale deployment potential.

The choice of this topic, *“The Impact of Energy Production from Wind and Solar Renewable Sources on the Environment. Case Studies in Romania”*, is motivated by the importance of analyzing the carbon footprint and the direct environmental impact of renewable energy projects, as well as comparing them with conventional energy sources, within a context where the adoption of sustainable energy solutions is sought to minimize climate change.

In the context of the European Green Deal, the most recent

meeting between states, aimed at establishing new measures in the fight against climate change, took place in November 2024, known as the United Nations Climate Change Conference 2024, COP29. During this meeting, discussions were resumed regarding the importance of transitioning to renewable energy sources, as well as expanding energy storage capacities and electricity grid infrastructure to ensure the stability of energy systems [1][2].

In recent years, Romania’s wind energy sector has experienced significant growth. With abundant wind resources, especially in the southeastern regions and Dobrogea, wind farms have become an important pillar of renewable energy production. Continuous investments in wind farms have contributed to diversifying the energy mix and reducing greenhouse gas emissions.

Romania’s solar potential has also attracted the attention of investors and authorities. PV systems have been widely implemented, with increasing capacities in both urban and rural areas. Incentive programs for solar energy production, together with continuously evolving solar technologies, have made solar energy an increasingly accessible and competitive source.

In this context, Life Cycle Assessment (LCA) represents a widely accepted methodology for evaluating the environmental impacts associated with energy production systems. In parallel, economic feasibility plays a crucial role in the decision-making process for energy investments. The Levelized Cost of Energy (LCOE) is a commonly used indicator that allows the comparison of different energy technologies based on their total lifetime costs relative to the energy produced.

This paper is structured as follows: Section 2 is dedicated to LCA concepts and the environmental impact of solar and wind energy production; Section 3 presents a case study on calculating the LCOE of a solar and wind system in Romania, followed by the conclusions section.

2. LIFE CYCLE ASSESSMENT LCA

In the context of growing concerns about sustainability and reducing environmental impact, both corporations and governments have recognized the importance of adopting rigorous methodologies for assessing the ecological impact of energy technologies. In this regard, Life Cycle Assessment (LCA) has become a fundamental tool for quantifying and interpreting the cumulative impacts

generated by renewable energy systems throughout their entire life cycle.

Life Cycle Assessment is a tool used to evaluate the potential environmental impact of a product throughout its entire life cycle, starting from the acquisition of raw materials, through the production and usage stages, and especially the management of waste generated after the product reaches its end of life [4].

LCA represents a quantitative methodology used to assess environmental impact. Its quantitative nature derives from the fact that the study involves collecting, modeling, and interpreting measurable data regarding resource consumption, such as raw materials, energy used in the process, and greenhouse gases, all of which have specific units of measurement.

Thus, LCA was standardized through ISO 14040:2006, which specifies the requirements for conducting an LCA study and its phases, which are four:

- Goal and scope definition phase.
- Inventory analysis phase (LCI – Life Cycle Inventory) – in this stage, input data is collected so that the study's objective can be achieved.
- Impact assessment phase (LCIA – Life Cycle Impact Assessment) – in this stage, additional information is gathered to help evaluate the LCI results and understand the environmental impact.
- Interpretation phase – decisions are made based on the results, in accordance with the defined goal and scope [5].

Figure 1 is representative of the analysis process, in accordance with ISO 14040:2006 Standard.

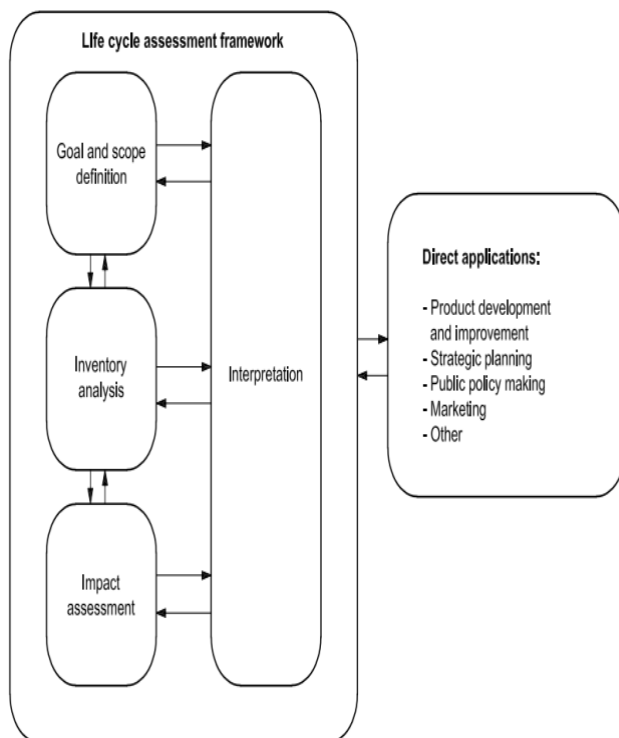


Figure 1. LCA Assessment ISO 14040:2006

Figure 2 illustrates the process through which a final product is analyzed using LCA.

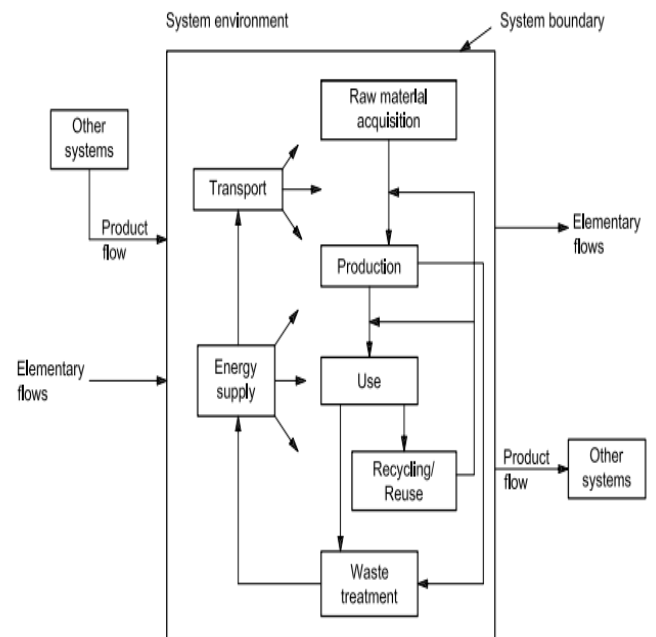


Figure 2. System Evaluation [5]

2.1 THE ENVIRONMENTAL IMPACT OF SOLAR ENERGY PRODUCTION

Solar energy represents one of the most accessible and promising sources of renewable energy in the global context of reducing the impact of greenhouse gases on the environment. Large-scale PV systems have become essential for meeting global objectives; however, their environmental impact is not completely neutral, considering the manufacturing of photovoltaic (PV) systems, the operation of solar farms, and the recycling of all equipment at the end of their life cycle.

To obtain PV systems, various raw materials are used, such as Silicon (Si), Cadmium (Cd), Copper (Cu), etc., which involve mining and extraction and purification processes [6]. Another factor that significantly contributes to environmental impact is the manufacturing stage of PV systems, as hazardous chemicals such as sodium hydroxide are used, which can affect workers' health or harm the environment if not properly managed and transported. Therefore, the carbon footprint of the PV systems manufacturing process can be considerable and is not neutral. During the operation of PV power plant, no greenhouse gas emissions are released; however, during the manufacturing process of PV modules, carbon dioxide emissions ranged between 14 and 73 g CO₂-eq/kWh, depending on the chosen technology [7].

Additionally, during the production of PV systems, water consumption is significantly higher compared to the operation phase of solar farms, where water is used only for maintenance by cleaning the PV systems. During the silicon cell manufacturing process, the water requirement ranges between 3.7 and 5.2 tons. However, the average

water consumption over the life cycle of PV power plants is 330 liters/MWh [8].

A major issue with this technology is the need for a large land area to install PV systems, which can have a significant impact on the environment, economy, and local communities. For example, land use density ranges between 1.5 and 2 hectares for each megawatt installed. This value is not fixed, as it depends on the land's topography, the module technology, and the layout to avoid shading [9].

To protect large investment lands, the Ministry of Agriculture and Rural Development amended Law 18/1991 in 2021, which previously prohibited the construction of PV power plants on land areas larger than 50 hectares. In 2024, this law was revised to avoid blocking the energy transition; however, the land category on which such parks are to be built must be of low quality [10].

Nevertheless, solar energy has a significantly lower environmental impact compared to conventional energy sources. Although there are challenges, starting from the production of materials for electrical equipment used to capture solar radiation and convert it into electricity, and ending with their disposal at the end of the photovoltaic park's life cycle, solar energy production is far less harmful compared to the polluting and destructive effects of fossil fuels. At the end of the life cycle, PV systems become waste, while burning fossil fuels produces ash, slag, and other toxic waste that is difficult to manage and dangerous for the environment.

2.2 THE ENVIRONMENTAL IMPACT OF WIND ENERGY PRODUCTION

The transition to renewable energy sources for maintaining energy security and independence, and the production of wind energy through wind turbines, represents a fairly accessible symbol of green energy. Compared to energy from conventional sources, this type of energy offers several advantages, starting with the significant reduction of carbon emissions into the atmosphere and the reduction of PM2.5 particle emissions, which represent a major issue for human health [11].

However, although the benefits of using wind energy are evident, its production process involves a series of stages that have a significant environmental impact. These stages include the manufacturing of wind turbines and primary equipment used to convert kinetic energy into mechanical energy and then into electricity, the transportation of turbines, the construction of the necessary infrastructure, and long-term maintenance, along with removing land from agricultural use and implicitly disturbing wildlife habitats through noise and the height of the towers.

The manufacturing of wind turbines is not neutral in terms of greenhouse gas emissions into the atmosphere; the largest amount of carbon dioxide is emitted during the

construction of the towers, accounting for 51% of the total carbon emissions over the entire life cycle of the wind farm. Additionally, greenhouse gases are emitted from the turbine foundations (approximately 20%), nacelle construction (approximately 16%), and blade construction (approximately 10%) [12].

Moreover, the foundation of wind turbines is made of cement, which is responsible for 8% of global CO₂ emissions; therefore, for a 4 MW turbine, the foundation alone emits 222 tons of CO₂ equivalent into the atmosphere [13]. However, according to new technologies, to improve the sustainability of wind turbine construction, reduce execution time, and, of course, minimize environmental impact, prefabricated foundations can be used. These components are manufactured in factories under strict quality control and then assembled on-site, compared to conventional foundations that are fully poured at the turbine site.

Wind turbines require significant amounts of materials for construction; for example, for 1 MW installed, an average of 66 tons of steel is used. Thus, for a 6 MW turbine, 369 tons of steel are needed. One ton of steel has a CO₂ emission factor of 1.91 tons, which means that a 6 MW wind turbine corresponds to emissions of 704.79 tons of CO₂ [14].

Another important aspect to mention is that, in addition to carbon emissions, the construction of wind turbines requires a significant volume of water, as this resource is needed from the foundations to the construction of access roads and cleaning of work areas on-site. During the operation phase of wind farms, water consumption is extremely low, approximately 4 liters/MWh, representing 0.6% of the total water used in a turbine's life cycle. The total water footprint for one MWh over the entire life cycle of wind turbines is 670 liters/MWh [15].

Moreover, during the construction of wind farms, noise is produced by the machinery involved in this process. Bulldozers generate about 115 dB(A), which is a unit of measurement that accounts for the sensitivity of the human ear to different frequencies; excavators generate about 117 dB(A), and compactors about 105 dB(A) [16]. Even during the operation of wind farms, wind turbines produce noise levels ranging between 30.7 and 43.4 dB(A) [12].

Another potential impact of wind turbines is that during winter they can freeze, and ice may fall, posing a risk to workers or injuring birds and animals nearby. Therefore, it is very important to implement a de-icing system for wind turbines.

A major impact of wind turbines is that ecosystems and natural habitats can be destroyed during construction and operation. Bat species and migratory birds may be exposed to the risk of collision with turbine blades. During the construction phase, in order to avoid exposing bats to collisions, this must take place during their inactive

period, which is between November and March; from April to October, they are active. Construction processes must minimize impacts related to noise, vibrations, and other elements that may disturb bats [17].

The construction of wind farms can also alter the migration routes of migratory birds, which can lead to additional energy consumption and affect the survival of certain bird species. Furthermore, if wind turbines are placed in areas where these migration corridors exist, the noise generated can affect birds by interfering with communication and prey detection. Additionally, air currents change, which can influence how birds fly around wind turbines [18]. Of course, the most important migration corridors are recorded in Natura 2000 sites, through which species are protected.

In Table 1 provide a comparative overview of key environmental characteristics of wind and solar energy, highlighting the main differences between the two systems across their life-cycle stages.

TABLE 1. COMPARATIVE ENVIRONMENTAL INDICATORS OF WIND AND SOLAR ENERGY TECHNOLOGIES

Indicator	Solar energy	Wind energy
Life – cycle	Manufacturing phase	Construction phase
GHG		
CO ₂ emission	14 – 73 CO ₂ -eq/kWh	Moderate
Water use	Manufacturing	Construction
Land use	High depending on the capacity of the project	Moderate
Noise	None	Low
Ecosystem impact	Land occupation	Birds/bats
Lifetime	Approximately 25 years	Approximately 20 years

3. STUDY CASE

A project must also be considered from the perspective of LCOE (Levelized Cost of Energy), which is an indicator that expresses the total updated cost of producing a certain amount of electricity (€/MWh), taking into account initial investments (CAPEX), operational and maintenance costs (OPEX), fuel costs (negligible in the case of PV and wind), and decommissioning costs, relative to the total amount of energy delivered over the installation's lifetime [19].

Thus, while LCA answers the question “How green is the energy produced?”, LCOE answers the question “How much does the energy produced cost?”. The two approaches are complementary and necessary within a framework focused on decarbonization and energy transition.

LCOE is standardized and internationally recognized; therefore, it is defined by the following general equation [20]:

$$LCOE = \frac{\sum_{t=1}^n \frac{I_t + M_t + F_t}{(1+r)^t}}{\sum_{t=1}^n \frac{E_t}{(1+r)^t}} \quad (1)$$

Where:

I_t = investments in year t (CAPEX);

M_t = operating and maintenance expenses O&M (OPEX);

F_t = fuel costs;

E_t = energy delivered to the grid in year t ;

r = discount rate.

n = economic lifetime.

LCOE applies to energy-generating technologies (such as solar and wind energy), while LCOS (Levelized Cost of Storage) is applicable to all storage systems. LCOE and LCOS are calculated using the formula above, the difference between them being the parameter E_t . In the case of LCOE, E_t represents the energy produced and delivered to the grid, whereas in the case of LCOS, E_t represents the energy actually discharged into the grid.

For this case study, we considered two calculation hypotheses:

1. Calculation of LCOE for a 100 MWp solar system;
2. Calculation of LCOE for a 99 MW wind system.

3.1 Calculation of LCOE for a 100 MWp Solar System in Romania

In this calculation scenario, we considered that the project is located in the Drăgănești Vlașca area, Teleorman, Romania, and the simulation regarding project profitability and solar resource was carried out using the Global Solar Atlas.



Figure 3 .PV Power Plant Location

As a result of the simulation, the following data were obtained:

- Direct Normal Irradiation (DNI) = The amount of solar radiation received directly on a surface oriented perpendicular to the sun's rays = 1305 kWh/m².
- Global Horizontal Irradiation (GHI) = The total solar radiation (direct + diffuse) received on a horizontal surface = 1402.1 kWh/m².
- Diffuse Horizontal Irradiation (DIF) = The diffuse component of solar radiation (light scattered by the atmosphere and clouds) on a horizontal surface = 635.3 kWh/m².
- For a photovoltaic system of 100 MWp, with a panel tilt of 34°, which is the optimal calculation angle, the total annual energy generated by this plant was calculated as 132.704 GWh/year.

In estimating CAPEX (Capital Expenditure), we considered the following general data (excluding land security, obtaining necessary permits, insurance, etc.):

TABLE 2. CAPEX ESTIMATION

Category	Total [mil. euro]
Photovoltaic modules	10
Civil works	15
Electrical works	10
Grid connection fee	3

For the OPEX (Operating Expenses) estimation, we considered O&M costs at 3% of CAPEX per year. Therefore, if CAPEX is €38 million, then OPEX = €1.14 million/year. Assuming that the average lifetime of a photovoltaic project is 25 years and fuel costs are zero, using Formula 1, the following LCOE results:

$$LCOE = \frac{51,3 \text{ mil. euro}}{1.546.000 \text{ MWh}} = 33,2 \text{ euro / MWh} \quad (2)$$

This shows that the project is profitable if the selling price of energy is higher than €33/MWh.

3.2 Calculation of LCOE for a 99 MW Wind System

In this case, we considered that the turbines are located around the locality of Horia, Constanța County. Using the Global Wind Atlas software, it was determined that there is sufficient wind resource in the area, making the project feasible, and the dominant wind direction is from the north and west, as shown in Figure 4.

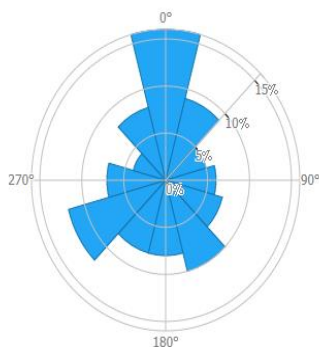


Figure 4. Wind Direction

For a turbine with a height of 150 m, the average wind speed in the analyzed area is 7.07 m/s, and the average wind power density is 373 W/m² [22].

In Figure 5, the mean wind speed at a height of 150 m for the analyzed area is illustrated, showing that 10% represents the best zones in terms of wind resource.

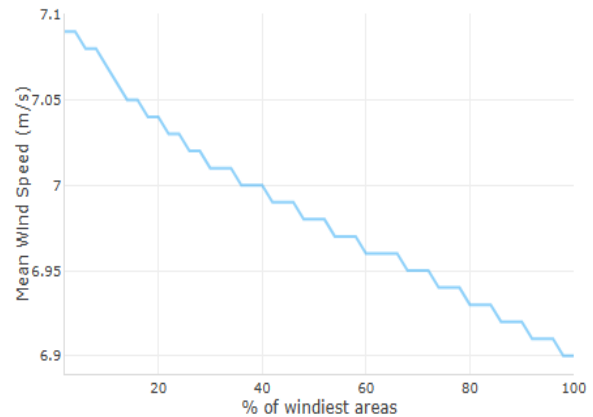


Figure 5. Mean wind speed for the analyzed area

In the calculation scenario, the following technical data were considered:

- Generic 4.5 MW wind turbines - IEC Class 2 (according to the Global Wind Atlas simulation) – total number of turbines = 22;
- Installed capacity = 99 MW;
- Tower height = 150 m;
- Rotor diameter = 136 m;
- Average wind speed = 7.07 m/s;
- Air density = 1.225 kg/m³;
- Total losses (cable losses, transformers, etc.) = 10%;
- Number of equivalent hours at nominal power per year = 3863 h.

Applied, the wind turbine power will have the following value:

$$P = \frac{1}{2} \cdot 1,225 \pi \left(\frac{136}{2} \right)^2 \cdot 7,07^3 \cdot 0,9 = 2,83 \text{ MW} \quad (3)$$

This is the theoretical instantaneous power calculated based on wind speed; it is not the nominal power provided by the wind turbine manufacturer.

The total energy production AEP (Annual Energy Production) is calculated using the following formula:

$$AEP = N_{WT} \times P \times T \quad (4)$$

N_{WT} = number of wind turbines;

T = number of operating hours per year.

Applied to the case presented above, AEP has the following value:

$$AEP = N_{WT} \times P \times T = 22 \times 2,83 \times 3863 = 240,5 \text{ GWh/y} \quad (5)$$

In estimating CAPEX (Capital Expenditure), we considered the following general data (excluding land security, obtaining necessary permits, insurance, etc.)

TABLE 3. CAPEX ESTIMATION

Category	Total [mil. euro]
Turbines (estimate: one turbine costs €3 million) 66	66
Civil works	30
Electrical works	10
Grid connection fee	5

For the OPEX estimate (Operating Expenses), we considered O&M costs at 3% of CAPEX per year. Therefore, if CAPEX is €111 million, then OPEX = €3.33 million/year.

We assume the average lifespan of a wind project is 20 years, and fuel costs are zero, resulting in the following LCOE:

Considering a discount rate of $r = 7\%$.

$$LCOE = \frac{3.33 \times 10^6 \times 12.247 + 111 \times 10^6 \times 0.258}{240.500 \times 10^3 \times 12.247} = 23,6 \text{ euro / MWh} \quad (6)$$

The project is profitable if the selling price of electricity is higher than €23.6/MWh. The cost assumptions used in the LCOE calculations are based on publicly available data from international reports and recent renewable energy projects developed in Romania.

4. CONCLUSIONS

Both wind and solar energy have a relatively low environmental impact in terms of greenhouse gas emissions and biodiversity compared to conventional energy sources.

However, neither wind nor photovoltaic energy is entirely impact-free. A significant negative factor is the manufacturing stage of PV systems and wind turbines. For PV, hazardous chemicals such as sodium hydroxide are used, which can affect workers' health or harm the environment if not properly managed and transported. In the case of wind turbines, the largest amount of carbon dioxide is emitted during the construction of the towers, accounting for about 51% of total carbon emissions over the entire lifetime of the wind farm. Solutions have been found to minimize this impact during construction, such as prefabricated foundations, whose components are manufactured in factories under strict quality control and then assembled on-site, compared to conventional foundations that are fully poured at the turbine site.

Simulations have also been carried out regarding the profitability of wind and solar projects, as decisions to develop renewable energy projects are analyzed from

multiple perspectives. One of the most important aspects is the need to decarbonize the energy sector by aligning Romania with European standards. Another key factor is the LCOE (Levelized Cost of Energy), an indicator that expresses the total discounted cost of producing a quantity of electricity (€/MWh), considering initial investments (CAPEX), operational and maintenance costs (OPEX), fuel costs (negligible for PV and wind), and decommissioning costs, divided by the total energy delivered over the lifetime of the installation.

The two scenarios are relatively similar to allow for a fair comparison of LCOE indicators. In the first scenario, LCOE = €33/MWh, while in the second scenario, LCOE = €23.6/MWh. The difference is significant because solar energy is not available at night, whereas wind energy can be available at any time of day, depending on wind resources.

The combined analysis of LCA and LCOE highlights the complementary nature of environmental and economic indicators in renewable energy assessment. While wind energy generally exhibits lower life-cycle greenhouse gas emissions, PV systems offer competitive LCOE values and more predictable energy generation profiles. These differences underline the importance of integrated evaluation frameworks when selecting renewable energy technologies, as decisions based solely on cost or environmental impact may lead to incomplete conclusions.

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